Statement of Research Interest

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My research interests focus on the geometry and topology of soft materials, in particular the effects of nonlinear elasticity on emergent structural and mechanical properties in complex systems. This encompasses a broad class of systems in several fields, from soft condensed matter physics to materials science to mechanical and biomedical engineering, with problems including programmable matter, pattern formation and elastic instabilities and the structure of membranes and interfaces.

Summary of Past and Current Research

• **Programmable Matter [1]** — The nascent technique of 4D printing has the potential to revolutionize manufacturing in fields ranging from organs-on-a-chip to architecture to soft robotics. By expanding the pallet of 3D printable materials to include the use stimuli responsive inks, 4D printing promises precise control over patterned shape transformations. My collaboration with the Lewis Lab turned a unique material and printing method – which enable the direct writing of local anisotropy into both the elastic moduli and the swelling response of the ink – into a predictive manufacturing technique for arbitrarily complex, morphable structures. By implementing a fully anisotropic model of thin film mechanics, not only can we predict the final transformed geometry from a given design, but my model generates the specific pattern of anisotropies needed to produce a target structure (see Fig. 1).

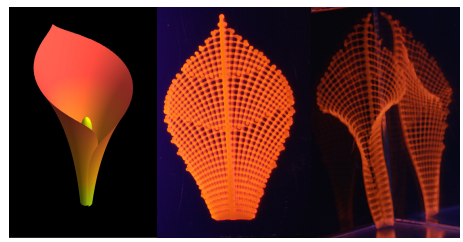

Fig. 1: From the local curvatures, we solve the inverse problem to design a print path which, upon emersion in water and swelling, strongly resembles our target structure.

• **Topological Defects and Nonlinear Two-Dimensional Elasticity** — The elastic coupling between topological defects, both dislocations and disclinations, and geometry helps to dictate both the properties and response of thin elastic sheets. At first glance, such an esoteric question has a remarkably wide range of real-world applications. The ability to create any curved surface merely by imprinting its metric into a flat sheet has great appeal for use in materials, manufacturing, and diagnostics applications. Freestanding smectic membranes provide new insight into the coupling between in-plane topological defects and surface curvature. The molecular splay distortions associated with disclinations act as sources of Gaussian curvature. Remarkably, positive disclinations are sources of *negative* Gaussian curvature and *vice versa* (see Fig. 2) [2]. Likewise, the goal of plastic and reconstructive surgery is to remove defects within the skin to excise malignancy, recreate damaged tissue or restore mobility. Successful surgeries are fundamentally based on understanding topological manipulations of the skin in the presence of an anisotropic elastic field [3]. Finally, the elastic instability experienced by compressing a perforated thin elastic film triggers nanoscale pattern formation which can be understood by a simple model of dislocation dipoles [4–6], which we have patented [7].

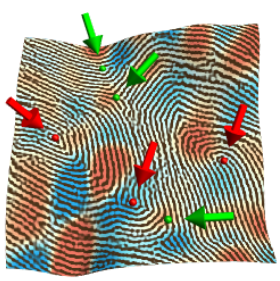

Fig. 2: In a free standing diblock membrane, $+\frac{1}{2}$ ($-\frac{1}{2}$) disclinations (red (green)), are sources of negative (positive) Gaussian curvature, K, shown in blue (orange).

• **Chirality and Hierarchical Assembly in Layered Systems** — Molecular chirality acts as a source of frustration in self-assembled, layered systems, such as smectic liquid crystals. In some situations, however, this frustration seeds the emergence of interactions at a wide range of

length scales, which lead to the development of complex, hierarchical structures. Understanding the microscopic interactions responsible for such intricate architectures is of paramount importance to being able do design self-assembled systems of arbitrary complexity. In my dissertation, I studied the morphological origins of one such system, the helical nanofilament phase (B4) of bent core smectic liquid crystals (see Fig. 3), as a new minimizer of the chiral Landau-de Gennes free energy [8]. Such chiral superstructures are not unique to bent core mesogens. Chiral assemblies also form from achiral constituents, such as block copolymers, amphiphiles and lipids. Assembly of a simple system – oblate ellipsoids in a solvent of spheres – sheds light on the emergence of chirality as a packing problem in the presence of steric constraints [9]. Additionally, such notions serve as building blocks to design the guided self-assembly of braids and weavings from filaments decorated with specific binding sites [10].

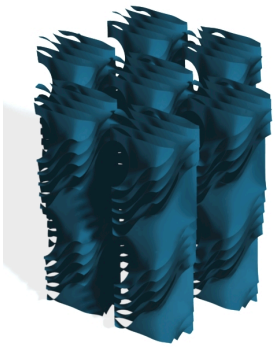

Fig. 3: The B4 is composed of a hexagonal array of coherently rotating helical bundles.

• **Past and Ongoing Collaborations** — It is my strong belief that science cannot progress in a vacuum – thus, I place the upmost importance on fostering collaborations with scientists in different fields and across the world. While I have always maintained close collaborations within my home institution, I actively seek joint projects with international scientists. Not only does this unite various points of view and specialties, but narrows the global conversation of science. My work on disclinations and curvature in free-standing diblock copolymers relied critically on the experimental expertise of Prof. Daniel Vega (Universidad Nacional del Sur, Argentina). Likewise, I currently maintain several international collaborations, including: tunable chiral minimal surfaces for photonics applications with Profs. Gerd Schröder-Turk (Murdock University, Australia and Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany) and Stephen Hyde (Australian National University, Australia), the emergence of hierarchical chiral architectures from achiral particles with simple interactions with Prof. Douglas Cleaver (Sheffield Hallam University, UK), and the use of topological defects to generate three-dimensional topography in woven and knitted materials with Prof. Eran Sharon (Hebrew University of Jerusalem, Israel).

Summary of Future Research Plans

The overarching theme of my research group will be to explore the effects of complex microstructure on emergent physical properties in complex soft materials. Exquisite control over microscopic properties, such as local elastic anisotropy or the geometry and topology of the microstructure, enables the design of functional local mechanical properties. In the following, I highlight three classes of system of particular interest: soft robotics, textile modeling and mechanics, and fiber based engineering.

• **Programmable Matter: Design, Implementation, and Logic** — With the advent of the field of soft robotics, research into soft actuators, sensors and electronics has blossomed. While the ultimate goal may still lie in the realm of science fiction, one feature still lacking from soft robotics that living things and hard robotics have acquired is the ability to locally process and respond to stimuli. Continuing in the vein of my prior work on programmable matter, building in multistimuli-responsive actuation, sensation and logic will allow for complex motion and interaction with the environment.

One immediate question arising concerns the possible configuration space for soft deformations with continuous curvature. How will the material properties and response effect the achievable

range of target structures? This is particularly interesting when the material shows a markedly different response to each of several stimuli. If the reaction to a given stimulus changes in the presence of a second stimulus, this now opens the possibility for non-commutative motion in a soft, classical system.

Local reconfigurability, feedback and sensation of soft robots will ultimately rely upon a logic system. As most soft actuators either rely on pneumatic or hydraulic power, it behooves us to design soft logic that runs upon these systems, thereby enabling sensing, processing and actuation simultaneously. Although some designs exist for soft logic currently exist, their size and cumbersome structure prohibit their implementation as soft microprocessors. Combining current additive manufacturing techniques, such as 3D printing, with directed self-assembly and biologically inspired devices, such as turgor pressure pumps used by trees, will vastly improve both efficiency and yield of such devices.

• **What a Tangled Web We Weave** — Spinning and weaving were some of the first technologies developed by man. These historical inventions continue to influence daily life, yet only at an empirical level do we understand the remarkable physical and material properties they can achieve. Spinning simply adds twist to fibers, vastly increasing tensile strength while maintaining flexibility. Weaving and knitting use single threads to generate durable yet pliant two-dimensional surfaces. Woven fabrics, inextensible along the warp and weft directions, have a soft shear direction which varies with the weave. While with a greater intrinsic elasticity, knits have two independent elastic moduli and a complex, out-of-plane bending response. Ultimately, the inherent anisotropy of both woven and knitted fabrics unites their descriptions. Building upon microscopic properties of the thread, from twist to chemistry to friction, my group will seek a set of local rules that control the global behavior of fabrics. Such a constitutive model will develop an understanding of the full range of fabric deformations, crucial for such applications as mechanoresponsive garments to biocompatible weaves and networks used in tissue engineering. Beyond technological advances, such a model will shed light on fundamental questions, such as polymer entanglement or the mechanical properties of biological tissue and networks.

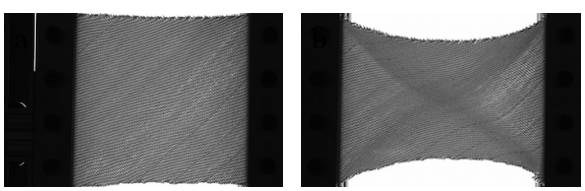

Fig. 4: A simple experiment in which twill fabric cut at 45° is stretched along the bias. The "X"-shaped darker regions occur due to the fabric's ubiquitous nonuniform strain response. This behavior, fundamentally different from rubber elasticity, is also responsible for the peculiar draping properties of fabrics.

Previous physical models for woven fabrics have been built from the machinery of isotropic linear elasticity. However, the ubiquitous warp-weft microstructure, which gives fabric both its inextensibility and soft shear, cannot be captured by such a description. In our model, the thread and its symmetries will play the central role. Taking this point of view, the mathematically based continuous metric description of elasticity theory breaks down.

Cloth-length threads impede stretch alonging the warp and weft directions, but in all other directions, the fabric has a finite give (see Fig 4). This becomes critical for the response to draping in three dimensions. In order to conform to a surface with nonzero Gaussian curvature, such as a human body, the fabric must both stretch and wrinkle. These properties depend on the angle of the applied force with respect to the warp and weft directions (see Fig. 5). Analogous methods have been used to improve upon current fabric models yet, since they rely upon standard

elasticity, these models do not describe all of the subtle response of cloth.

The omnipresence of computer animation and graphical physics simulation renews the need to completely quantify the mechanics of fabrics, textiles and clothing. With computational competition between the precision of the microscopic model and the efficiency of the continuum model, a comprehensive description of fabrics will combine an atomistic thread-level description with bulk mechanics using adaptive dynamics algorithms. Much as the shallow water equations emulate believable hydrodynamics without the need of fullscale Navier-Stokes simulations, so too will our constitutive fabrics model enable the rapid modeling of realistic fabrics and garments for the video game and computer animation industries. The challenge comes from incorporating details at all scales of the problem. The local weave or stitch pattern influences drape, texture and porosity, which in turn, affect the interactions with the factors in the environment, such as lighting, wind and motion.

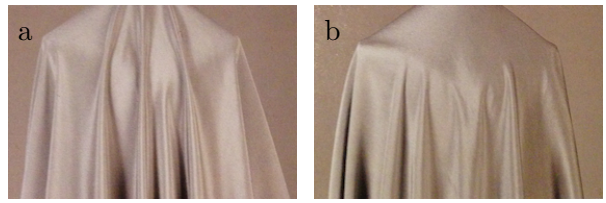

Fig. 5: Something as simple as orientation can have a massive effect on the ability of a fabric to conform to a curved surface. On the left, the warp direction is parallel to the floor. While, the right figure is draped with warp and weft oriented at $\pm 45°$. *Images*: The Editors of *Threads Magazine*, *SewBasic: 34 Essential Skills for Sewing with Confidence*, The Taunton Press, Newton, CT (2002).

• **Designing Material Properties from the Ground Up** — How do you create stretching from an inextensible material? Can we make a material that drapes any shaped object? What can historic engineers teach us about modern composites and metamaterials? These are just a sampling of questions my lab will endeavor to explore. Combining the artistry of dressmakers and couturiers with the mathematical rigor of anisotropic elasticity theory creates a novel framework for the design and fabrication of modern functionalized textiles and garments.

With the advent of textiles, came the diversification of clothing, making garments both functional and fashionable. Once solely the realm of the couturier, the need to transform flat two dimensional surfaces into wrappings for complex three-dimensional curved structures persists to the modern era. Composites and building wraps in architecture, energy efficiency and insulation, flexibility and functionality of protective garments and body armor represent just a handful of applications that seek to design the best fit while minimizing seams and defects that impede functionality. Likewise, optimizing the material for the function relies on balancing many qualitative properties of weaves – durability, drapability, porosity, smoothness and shine.

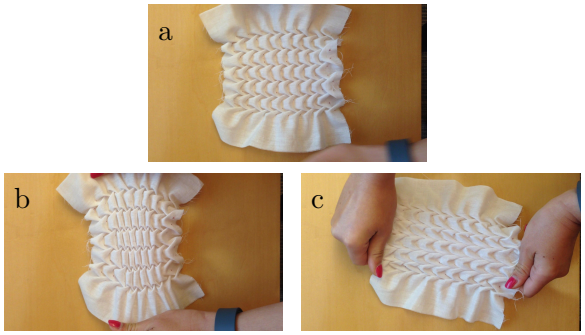

Fig. 6: In modern smocking, a regular array of knots constrains small folds. Nonparallel folds results in biaxial emergent elasticity.

One might be surprised to learn that the first mechanical metamaterial was invented during the middle ages. The medieval embroidery known as smocking uses knots to constrain a regular set of pleats, thereby converting local bending energy into bulk stretching energy. Modern smocking techniques sacrifice maximal extension to give the material biaxial stretch (see Fig. 6). This quickly becomes a complex mathematical question coming from the strict constraints of rigid origami imposed by the inextensibility of paper. Relaxing these constraints using woven fabrics opens up a zoo of possible configurations. Working with model and experimental systems, my group will design and create materials, such as mechanical

metamaterials and auxetics, with emergent properties due to imposed microstructure.

Modern technology presents a new set of problems and challenges to surmount. This brings to light many possible potential collaborations with experimental groups from around the world, including an ongoing attempt to fabricate functional nano-cloth [11]. The seeming lack of natural analogues to braiding and weaving opens the door for synthetic systems to attempt weaving on a multitude of length scales. The ability to control weave, functionality and therefore material properties of cloth at nano- or micro-scales would be an engineering feat. Be it through directed self-assembly, additive manufacturing, DNA origami, or chemical synthesis, several existing techniques may hold the key to unlocking this new class of materials.

References

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